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Conceptual Design of 2-in-1 Nb3Sn Arc Quadrupole Magnets for VLHC

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Abstract - The note describes a conceptual magnetic and mechanical design of the double aperture Nb3Sn quadrupole magnets with cold iron yoke being developed at Fermilab for VLHC. The design is based on a two-layer shell-type Nb3Sn coil with the inner bore diameter of 43.5 mm. Both designs with vertical and horizontal bore arrangements have been developed.

I. INTRODUCTION

Magnetic system of the high field stage of VLHC (VLHC-2) is a FODO structure with separate functions. It consists of arc dipole and arc quadrupole magnets, multipole correctors and special magnets. The conceptual designs of arc dipole magnets developed for VLHC-2 at Fermilab are described in [1]. All these designs utilize the 2-in-1 approach but use a different coil geometry (cos-theta or block common coil), different bore arrangements (vertical or horizontal) and different iron yoke designs (cold or warm). All magnets provide an accelerator field quality in the required operation field range. The final choice of magnet design for VLHC-2 will depend among other things on results of magnet R&D program that will provide the data on magnet performance and cost.

Arc quadrupole magnets are not independent objects. Their design and parameters have to be coordinated with the design and parameters of the arc dipole magnets and machine magnet structure including IR optics. This note presents a description of the conceptual design of arc quadrupole magnets to be used with different arc dipoles in VLHC-2 arc cells. Based on two possible IR optics in VLHC-2 with flat or round beams, two possible current/field configurations corresponding to different magnet functions have been considered. One for the vertical bore arrangement and flat beam optics provides the FF or DD function of each quad with respect to the corresponding beam and another one for the horizontal bore arrangement and round beam optics provides the FD/DF function. These two cases differ by the current directions in the coils and the flux distribution in the iron yoke.

II. COIL

All quadrupoles described below utilize similar superconducting coils. The quadrupole coil cross-section is shown in Figure 1. The design of the coil utilizes the same cable and employs the same design principles as the Nb3Sn cos-theta dipole magnets [2]. The coil bore diameter is 43.5 mm. Each coil quadrant consists of 13 turns. Total number of tuns is 52 and coil area is 24.1 cm^2. The inter-layer spacer thickness is 0.28 mm and the thickness of the additional mid-plane insulation layers is 2×0.125 mm. Each coil quadrant has a floating pole and two wedges in the inner layer, which allow minimizing the low order field harmonics. An 11 mm wide pole spacer is quite comfortable for coil winding.

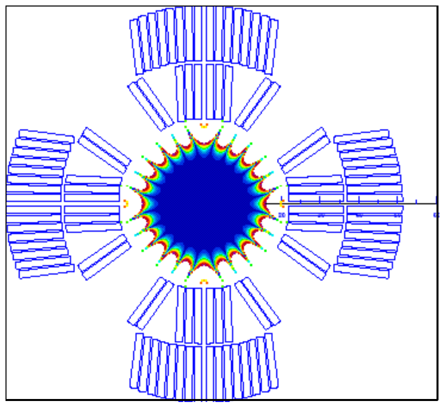

Figure 1. Quarupole coil cross-section.

Geometrical harmonics at R_{ref}=10 mm optimized for this coil for the yoke inner radius of 72 mm and the iron permeability of 1000 are: b6=-0.00028, b10=0.00038 and b14=0.01322. The coil ends have the same block-wise layout of turns as in the magnet body. The end block positions are optimized to reduce the maximum field in the end area with respect to the straight section and to improve end field quality.

The coil utilizes a keystone Rutherford-type cable made of 28 Nb_3Sn strands, each 1 mm in diameter. The width of bare cable is 14.24 mm, the middle thickness is 1.800 mm and the keystone angle is 0.91degree. Cable is insulated with ceramic insulation designed to withstand a long high-temperature heat treatment. The nominal thickness of the cable insulation is 0.25 mm. Both layers of each coil are made from one cable piece without an inter-layer splice.

The magnet straight section is prestressed and mechanically supported by means of Nitronic 40 stainless steel collar laminations. Collar thickness of 20 mm was scaled from the design of the LHC IR quadrupoles developed at Fermilab [3]. Coil support structure based on these collars will be able to keep the coils under compression with the stress in the coil less than 150 MPa in the operation field gradient range [4]. Four pairs of tapered keys lock collar laminations in two perpendicular directions. Prestress and mechanical support of the magnet ends is provided by thick aluminum end cans. No additional radial support from the iron yoke is required.

III. VERTICAL BORE ARRANGEMENT

The 2-in-1 arc quadrupole magnet design with vertical bore arrangement will be used togather with the common coil dipole magnet [1]. The common coil dipole design optimized for the react and wind fabrication technique dictates the bore separation distance. The thickness of the collar laminations determine the yoke inner radius. Two collared coil coils are placed inside the round holes of 144 mm in diameter inside the common iron yoke and separated by 290 mm. The iron yoke was split vertically into two pieces to allow assembly of two coils in one yoke. In order to reduce the effect of gap variation on the field quality, the vertical gap between two iron pieces is always closed. The yoke laminations also feature special cutouts for fabrication purposes.

The case with FF functions is a baseline design for the VLHC-2 with flat beam optics. In this case the vertical component of the magnetic field in the yoke midplane is zero. Due to the common iron yoke there is a magnetic coupling of two quadrupole coils. Special holes were used for minimization of coupling and iron saturation effect. Their position and size as well as the yoke outer diameter were optimized at the above boundary conditions to provide the required field quality and low fridge fields in the wide field range up to the maximum operation field. Figure 2 presents the flux distribution in the optimized 2D cross-section of the quadrupole magnet with FF functions.

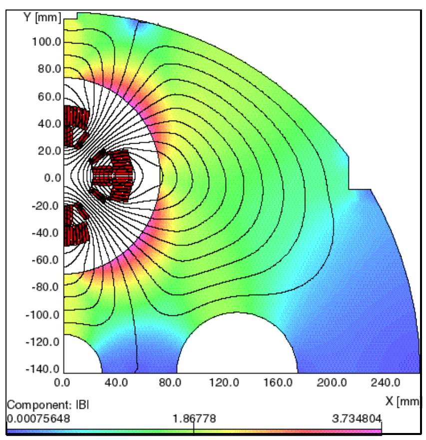

Figure 2. Flux distribution for FF 2-in-1 configuration.

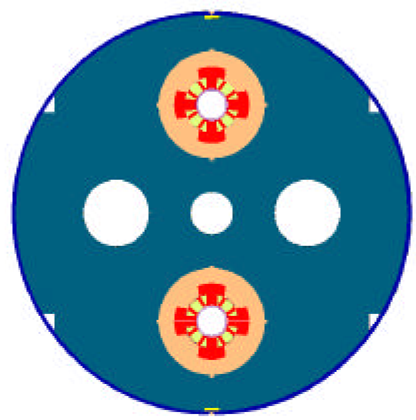

Figure 3. Cold mass cross-section.

The optimized quadrupole cold mass cross-section is shown in Figure 3. The collared coils are centered inside the iron yoke with the help of special alignment keys. The optimized yoke outer diameter is 530 mm. The two-piece iron yoke is surrounded by two-piece stainless steel skin. Two skin shells are welded under some tension to provide tight contact of the iron yoke blocks. To restrict coil longitudinal motion under Lorentz forces, applied to the coil ends, two stainless steel end plates welded onto skin are used.

The main parameters of the 2-in-1 quadrupole magnet with vertical bore arrangement are summarized in Table 1.

IV. HORIZONTAL BORE ARRANGEMENT

The 2-in-1 arc quadrupole magnet design with horizontal bore arrangement will be used together with the VLHC-2 cos-theta dipole magnets [1]. The bore separation distance is the same as in cos-theta dipoles and the yoke inner radius is as in the previous case. Thus two collared coils are placed inside the round holes of 144 mm in diameter separated by 180 mm inside the common iron yoke. The iron yoke was split horizontally into two pieces to allow assembly of two coils in one yoke. The gap between two iron pieces is always closed in order to reduce the effect of gap variation on the field quality. The yoke laminations also feature special cutouts for fabrication purposes.

The baseline design of arc quads with horizontal bore arrangement is FD configuration adjusted for the round beam optics. In this case the vertical component of the magnetic field trough the vertical plane of symmetry of the iron yoke is zero. Special holes and yoke OD were optimized with these boundary conditions to reduce the iron saturation effect. Figure 4 presents the flux distribution in the optimized 2D cross-section of the 2-in-1 arc quadrupole magnet with horizontal bore arrangement and FD functions. The optimized quadrupole cold mass cross-section is shown in Figure 5.

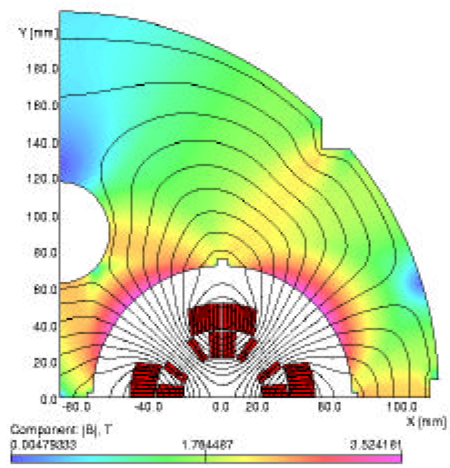

Figure 4. Flux distribution for FD 2-in-1 configuration.

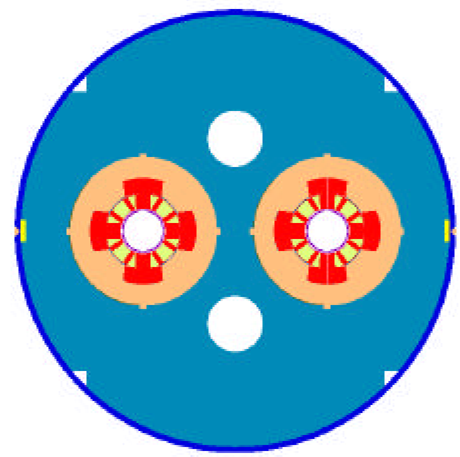
Figure 5. Cold mass cross-section.

The main parameters of the arc quadrupole magnet with FF or DD functions are summarized in Table 1.

V. MAGNET PARAMETERS

Main parameters of the 2-in-1 quadrupole magnets with vertical and horizontal bore arrangement are summarized in Table 1.

Table 1. Calculated Quadrupole Parameters.

Bore arrangement	Vertical	Horizontal
Configuration (function)	FF/DD	FD/DF
G_{nom}, T/m	400	400
I_{nom}, kA	27.2	27.3
Aperture, mm	43.5	43.5
Aperture separation, mm	290	180
Iron yoke OD, mm	530	420?
Transfer function @ 400T/m, T/m/kA	14.69	14.67
Stored energy @ 400T/m, kJ/m	2×209	2×209
Inductance @ 400T/m, mH/m	2×0.565	2×0.562

The inductance and stored energy vs the current in the coil for both quadrupole designs is shown in Figure 6.

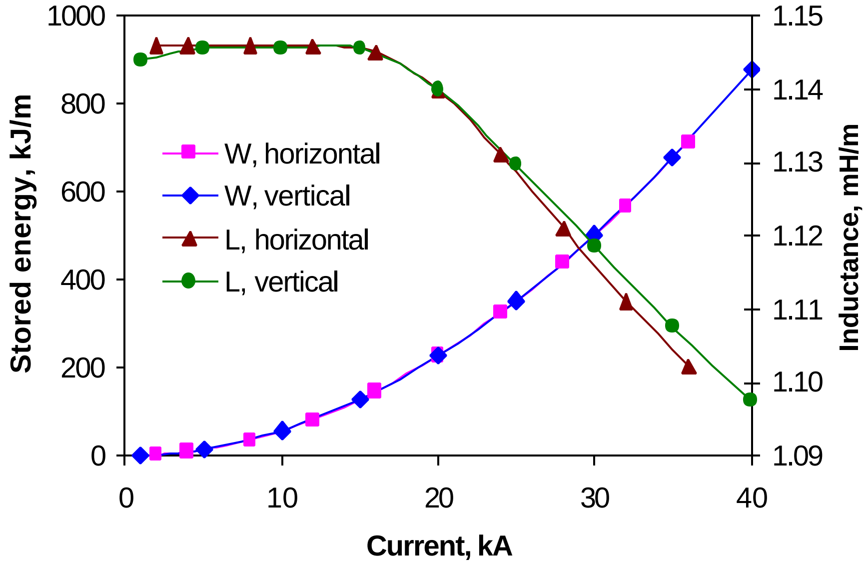

Figure 6. The inductance and the stored energy vs the current in the coil.

Maximum (quench) field gradient in the quadrupole aperture @ 4.2 K vs. the critical current density of Nb_3Sn strand in the coil for two different values of Cu:nonCu ratio is shown in Figure 7. At the 10% I_c degradation, a nominal field gradient of 400 T/m with 10% margin will be achieved in both designs using the R&D strands with J_c(12T,4.2K)=3 kA/mm^2 and Cu:nonCu=1.2:1 required for magnet quench protection [5].

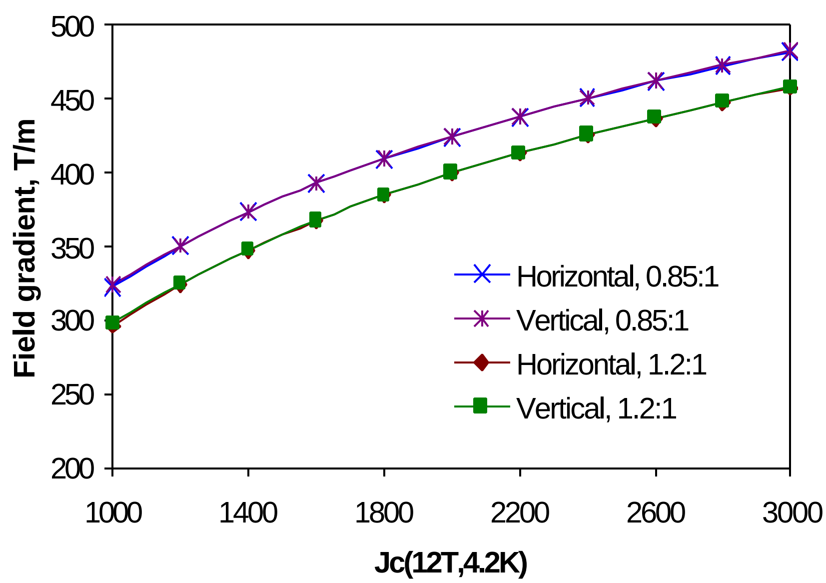

Figure 7. Maximum (quench) field gradient in the magnet aperture @4.2K vs. the critical current density of Nb_3Sn strand in the coil at the reference field.

Magnetic field in the quadrupole bore is described according to the expression

$$B_y(x,y) + iB_x(x,y) = 10^{-4} \times B_2 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1},$$

where $B_x(x,y)$ and $B_y(x,y)$ are horizontal and vertical field components, $B_2 = G \cdot R_{ref}$ is the main quadrupole component, R_{ref} =1 cm is the reference radius; b_n and a_n are the normal and skew harmonic coefficients.

Calculated geometrical harmonics and their RMS spread at 1 cm radius for ±50 μm random coil block displacements for the arc quadrupole are summarized in Table 2.

Table 2. Systematic and random geometrical harmonics at 1 cm radius, 10^{-4}

Harmonic number, n	Vertical bore arrangement			Horizontal bore arrangement		
	Systematic, bn	Systematic, an	RMS, $\sigma_{a,b}$	Systematic, bn	Systematic, an	RMS, $\sigma_{a,b}$
3	-	-	1.82	-	-	1.82
4	-	-	0.82	-	-	0.82
5	-	-	0.38	-	-	0.38
6	-0.0003	-	0.19	-0.0003	-	0.19
7	-	-	0.07	-	-	0.07
8	-	-	0.026	-	-	0.026
9	-	-	0.013	-	-	0.013
10	-0.0038	-	0.001	-0.0038	-	0.001

Systematic harmonics and harmonics RMS spread shown in Table 2 is the same for both quadrupoles since both magnets utilize the same coil design.

The effect of iron saturation at high field gradients on magnet transfer function and low order field harmonics is shown in Figure 8.

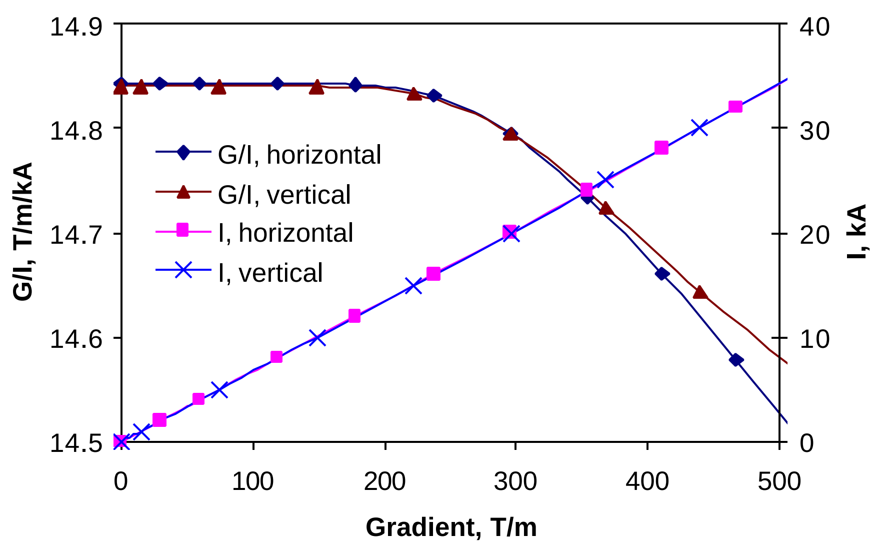

Figure 8. Transfer function G/I and coil current I vs the field gradient in the aperture.

The effect of iron saturation at high field gradients on the low order field harmonics and magnetic coupling effect are shown in Figure 9.

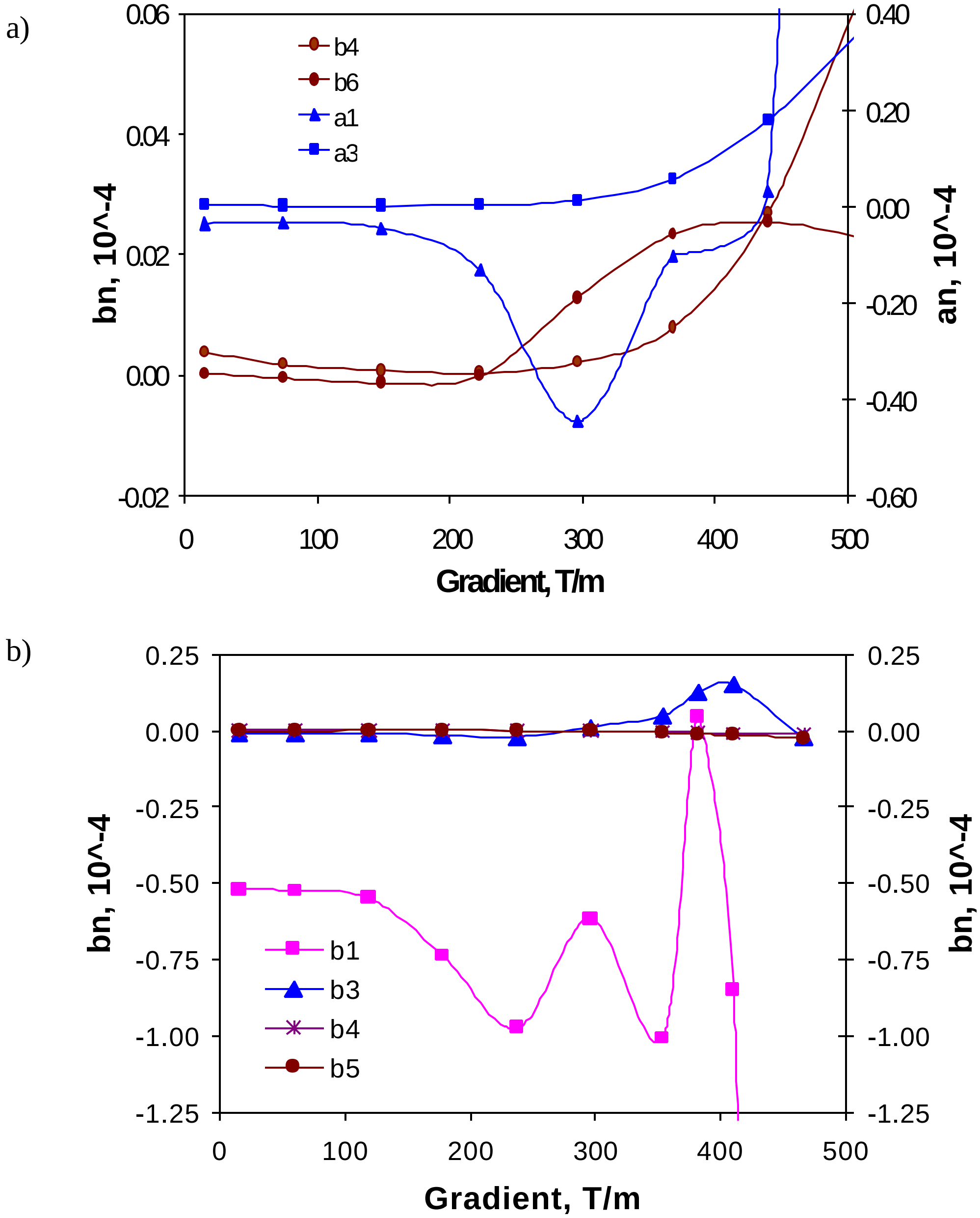

Figure 9. Low order field harmonics vs the field gradient in the aperture for the quadrupole with vertical (a) and horizontal (b) bore arrangement.

As it was mentioned above, the nominal configuration of the 2-in-1 quadrupole with vertical bore arrangement is FF or DD which suitable for the flat beam optics. In case of round beam optics arc quadrupole configuration must be FD or DF. Low order harmonics for the quadrupole with vertical bore arrangment and FD configuration vs. bore field gradient is shown in Figure 10. As it can be seen from the plot, some additional optimization of the iron saturation effect and magnetic coupling has to be done in the described design.

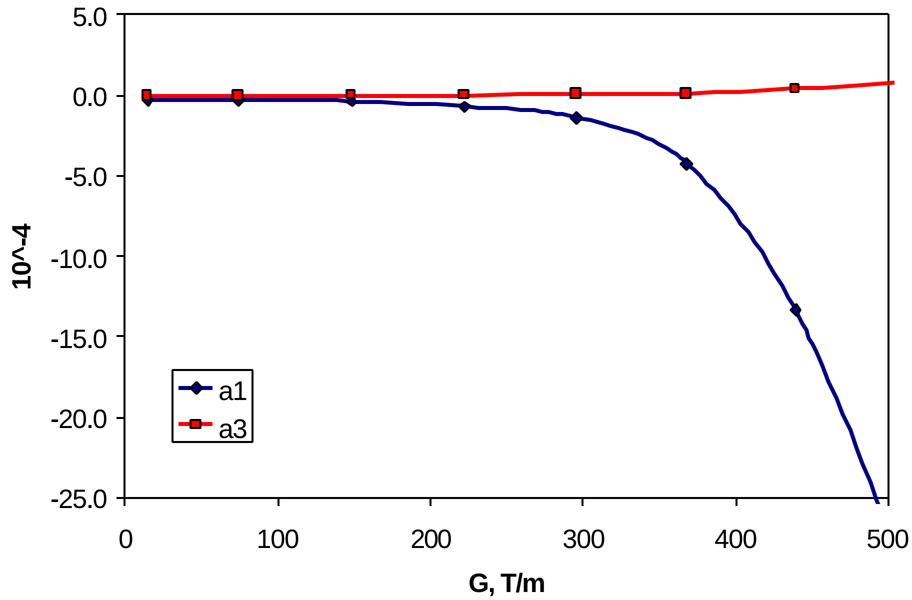

Figure 10. Low order harmonics for the quadrupole with vertical bore arrangment and FD function.

The effect of superconductor magnetization on the quadrupole field quality is shown in Figure 11. This effect is the same for both designs since it determined basically by the coil geometry, inner yoke radius and superconductor properties. Calculation were performed for the Nb3Sn strands with the critical current density Jc(12T, 4.2K)=2 kA/mm^2 and effective filament diameter d_{eff}=100 μm with and without correction. As it can be seen, field quality is significantly deteriorated at low field gradients due to the high coil magnetization. The passive correction with 0.1 mm thick iron strips [6], placed as shown in Figure 12 on the inner layer wedge (left) or on the beam pipe (right), allows reducing this effect to the acceptable level.

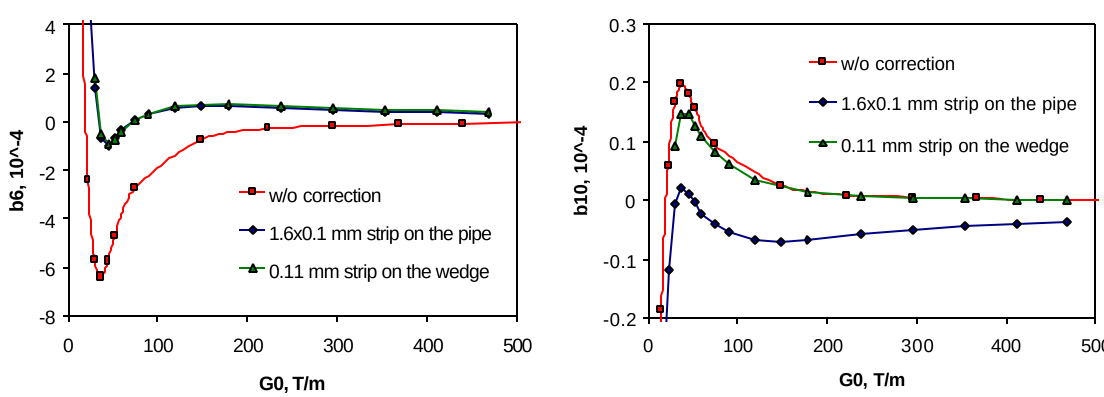

Figure 11. Effect of coil magnetization effect in arc quadrupole magnet on the low field harmonics b6 (left) and b10 (right).

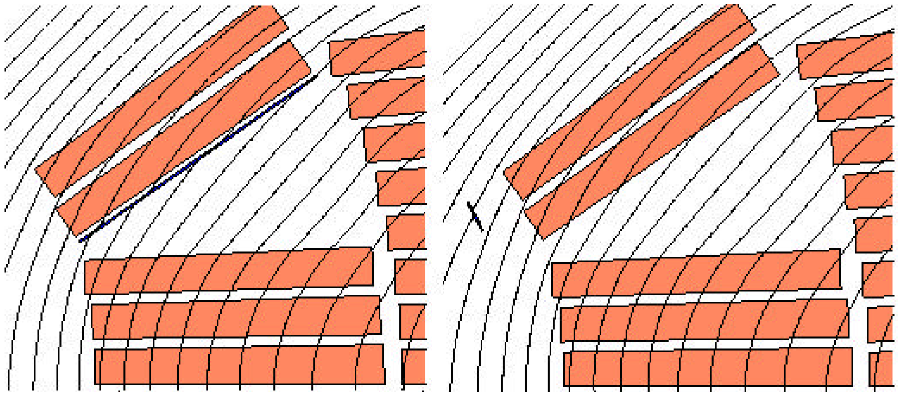

Figure 12. Correction strip position in the quadrupole magnet: on the wedge (left) and on the beam pipe (right).

VI. CONCLUSIONS

The designs of the arc quadrupole magnets with horizontal and vertical bore arrangement described above meet the VLHC requirements. They provide an operation field gradient range from 45 to 400 T/m with sufficient critical current margin. A reduction of the quadrupole transfer function is about 1% at the nominal field gradient of 400 T/m which is much less than the reduction of the dipole transfer function. To provide constant G/B ratio in the operation field range, the arc quadrupole magnets will be powered independently from arc dipole magnets, and their current will be appropriately regulated. The iron saturation effect on the normal and skew low order harmonics is effectively suppressed in the field gradient range up to 400 T/m by optimizing the yoke size and correction hole geometry. Coil magnetization effect at field gradients G>45 T/m minimized by using a simple passive correction based on the iron strips and/or by reducing the effective filament diameter in Nb3Sn strands.

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